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Identifying habitual sled-pulling in dogs through the study of entheseal changes

Jessica Sick [a], Angela R. Lieverse [a], Tatiana Nomokonova [a], Robert J. Losey [b,*]

[a] Department of Anthropology, University of Saskatchewan, 55 Campus Drive, Saskatoon, SK, S7N 5B1, Canada
[b] Department of Anthropology, University of Alberta, 13-15 Tory Building, Edmonton, AB, T6R 3H8, Canada

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ABSTRACT

Sled dogs are among the most iconic animals of the North, and their efforts in pulling sleds facilitated trade and subsistence practices that sustained many Indigenous groups for thousands of years. Unfortunately, the history of dog sledding is difficult to trace in archaeology. The identification of dog sledding in the past has been mostly addressed through the association of dog skeletal remains with material parts of sleds and harnessing equipment. However, there is currently no method for identifying sled-pulling activity directly from canid remains. This article introduces a new visual scoring manual for entheseal changes to address this gap in knowledge. Entheseal changes are morphological variations to entheses, which are muscle, tendon, and ligament attachment sites on bone. They have been used to reconstruct past activity in humans and, more recently, reindeer and equid remains, but never in canids. This method was developed for thirteen entheses on the forelimb and hindlimb using 74 working sled dogs, non-working pet dogs, and wild canids. Visual scores were compared to examine the effect of activity on entheseal changes, but also confounding biological factors such as age, sex, and body size. Observer error tests were also conducted to determine the method's precision and repeatability. The results show that sled dogs have significantly higher scores than non-working canids, especially for seven attachments. This suggests that entheses are morphologically sensitive to habitual sled-pulling, though some attachments are better indicators of working activity than others. Overall, these findings demonstrate that the method can differentiate sled dogs from pet dogs and wild canids and is a useful tool for identifying sled-pulling activity in archaeological canid remains. Furthermore, this method will help to better understand the history and development of human-dog relationships in the North.

1. Introduction

Dogs have accompanied humans in the North for thousands of years as active participants in daily life (Pitulko and Kasparov, 2017; Bergström et al., 2020; Sinding et al., 2020). Historically, they served many important roles, acting as valued companions and co-workers, but were also used as food sources and sacrificial offerings (Losey et al., 2018a, 2018b). Pulling sleds is perhaps the most important and iconic practice for dogs in the North, as this mode of transport significantly enhanced social interaction, trade, and subsistence practices (Ameen et al., 2019; Egevang et al., 2020; Losey et al., 2018a; Losey et al., 2018; Morey and Kim, 2002; Pitulko and Kasparov, 2017; Vitale et al., 2023). However, the history and development of dog sledding has proven difficult to trace. Evidence typically used to infer dog sledding includes the presence of dog remains, the body sizes of these dogs, and the identification of gear such as harnesses, buckles, and sleds, particularly when the latter is found in association with dog remains. For example, the earliest evidence of dog sledding is potentially found at Zhokhov Island in the Eastern Siberian Arctic around 9000 years ago, where remains of multiple dogs were unearthed in association with wood sled parts and possible harnessing equipment (Pitulko and Kasparov, 2017). Possible dog sledding artifacts remained rare in Siberia until ~2200 years ago, and larger dogs and sledding gear resembling that used by recent Inuit groups appeared in portions of the North American Arctic only 1–2000 years ago (Ameen et al., 2019; Friesen and Mason, 2016; Losey et al., 2018b; Morey and Kim, 2002; Pitulko and Kasparov, 2017; Vitale et al., 2023). This spotty and intermittent archaeological history of dog sledding remains challenging to interpret.

This paper introduces a new method for tracing the history of dog sledding that focuses on entheseal changes on canid skeletal remains.

* Corresponding author.
E-mail address: robert.losey@ualberta.ca (R.J. Losey).

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Entheseal changes (EC) are morphological variations to entheses, the attachment sites for muscles and ligaments on bone. The link between EC and activity is based on the concept of bone functional adaptation, where skeletal tissue remodels over time to disperse mechanical stress more effectively (Ruff et al., 2006; Wolff, 1986). Essentially, entheses that show more morphological changes are attributed to having undergone greater amounts of mechanical loading, thus allowing researchers to discern patterns of activity in archaeological contexts (Jurmain et al., 2012). While EC reflect bone remodelling in response to biomechanical stress, they can also be affected by confounding systemic factors such as age, biological sex, body size, and genetic variation (Henderson et al., 2017; Jurmain et al., 2012; Sick, 2021).

Entheseal changes have been extensively studied in human remains (e.g., Henderson et al., 2013, 2017; Jurmain et al., 2012; Lieverse et al., 2013) and recently studied in non-human animals such as reindeer (*Rangifer tarandus*) (Hull et al., 2020, 2024; Niinimäki and Salmi, 2016, 2021; Salmi and Niinimäki, 2016) and equids (Bindé et al., 2019) to distinguish working behaviour. Compared to other skeletal methods for activity reconstruction, such as the study of cross-sectional geometry and osteoarthritis, EC can inform on more precise activities (e.g., Karakostis et al. 2020), providing more detail regarding occupation, tool use, or other activities (e.g., Jurmain et al., 2012; Kunze et al., 2022; Lieverse et al., 2013; Sick, 2021; Yonemoto, 2016). Additionally, EC analysis is non-invasive and can be applied to fragmented remains, which is advantageous for application to archaeological materials (Jurmain et al., 2012; Sick et al., 2022). Previous EC research suggests that habitual activity is best observed on entheses when such behaviours are strenuous and lifelong, especially when they begin in early development (e.g., Turcotte et al., 2022). This makes sled dogs ideal candidates for study because their working lives normally include intense daily training that begins in juvenescence and continues until the individual can no longer work effectively (Bostelmann, 1976; Shannon, 1997; Loovers, 2018; McHugh, 2013).

Non-metric visual scoring methods are the earliest and most popular for EC analysis, typically involving ranked scoring systems that categorize the range and expression of entheseal morphology (e.g., Hawkey and Charles, 1995; Henderson et al., 2013, 2017; Villotte et al., 2010). These methods have demonstrated reliability in identifying activity-related patterns in past human populations (e.g., Henderson et al., 2013, 2017; Lieverse et al., 2013; 2013; Yonemoto, 2016) and differentiating working and non-working behaviour in archaeological reindeer (Hull et al., 2024). Furthermore, compared to more recent quantification methods such as those using 2D and 3D scans (e.g., Wilczak, 1998; Karakostis, 2015, 2022; Karakostis et al., 2017, 2018; Karakostis and Lorenzo, 2016; Karakostis and Harvati, 2021; Nikita et al., 2019; Nolte and Wilczak, 2013), non-metric visual methods are low cost and readily applicable to archaeological remains.

This paper is the first to introduce an EC scoring system for canid remains as a way to reconstruct sled-pulling activity. The goals of this research are twofold. First, we demonstrate that our EC scoring method can identify sled-pulling activity and differentiate working from non-working and wild canids. Second, we identify the extent to which confounding factors such as age, sex, and body mass affect canid entheseal morphology. This paper does so by comparing scores of 13 entheses on the appendicular skeletons of 74 canids (modern Inuit sled dogs, pet dogs, and wild canids). We discuss the development of the scoring system, the methods used for analysis, and repeatability through inter- and intra-observer error tests.

2. Materials and methods

The sample (n = 74) in this study (Table 1; Appendix A) includes 22 Inuit dogs with known life histories of sled-pulling. These sled dogs lived on Ellesmere Island, Canada, and were collected in the 1960s by Dr. Milton Freeman, who worked directly with them and documented their use. These samples are curated at the Canadian Museum of Nature (CMN) and have age and sex information. Dr. Freeman processed and collected these specimens while conducting post-doctoral research on Inuit dog sledding energetics on Ellesmere Island. In interviews with Dr. Freeman, he stated that the dogs were employed in pulling traditional low sleds for daily hunting trips and other regional travel during the mid-to-late 1960s, around the period when snowmobiles were first introduced to Ellesmere. The dogs were never used for racing. The sample also includes 20 pet dogs and 32 wild canids (22 wolves, six coyotes, and four coydogs) curated at the University of Alberta (UA), Royal Alberta Museum (RAM), and University of Saskatchewan (USask). Sex and age-at-death were known for all pet dogs, and sex was known for the wild canids, the latter all adults.

There is no existing EC scoring method for canids, so previous scoring systems developed for humans (Henderson et al., 2017; Villotte et al., 2010), reindeer (Niinimäki and Salmi, 2016) and equids (Bindé et al., 2019) served as the basis for this method. Following standard practice in human EC research, fibrous entheses (FE) and fibrocartilaginous entheses (FCE) were considered separately because they have different morphological characteristics and tissue types at their attachment sites (Henderson et al., 2017; Villotte et al., 2016). Likewise, we adopted standard definitions from human research (Henderson et al., 2017; Villotte et al., 2016) but modified them to accommodate unique canid entheseal morphology and anatomical terminology (Evans and Lahunta, 2013; Smith, 1999). These modifications are consistent with observations made in other non-human EC studies, where 'normal' entheseal morphology and range of expression were found to differ from that of humans (Bindé et al., 2019; Niinimäki and Salmi, 2016), likely reflecting developmental differences in locomotion (Appendix B). For example, 'erosion,' commonly observed in human entheses, was rarely observed on reindeer and equids, and was not present in any discernible pattern on our canid samples. It was therefore excluded from this study.

Entheses were chosen for study based on two criteria: 1) involvement in mechanical loading during sled pulling activities; 2) demonstrated morphological variability. In total, 13 long bone entheses were considered (Fig. 1). Muscles associated with the entheses under study were examined using canine cadavers to better understand their structure and anatomical position on dry bone. A visual scoring method was developed using the pet and sled dog specimens (n = 42). Each enthesis was classified into two or three ordinal categories reflecting the degree of EC expression being described, and ranked based on its own range of

Table 1
Summary of canid specimens used in this study.

Species	Collection[a]	Sex[b]	Age	Weight	Activity History	Total
Sled dog (*C. familiaris*)	CMN	16M, 5F, 1U	1–8 years	17 known (23–49 kg)	Sled-pulling	**22**
Pet dog (*C. familiaris*)	UA, RAM	12M, 7F, 1U	1.25–16 years	15 known (11–64 kg)	Non-working	**20**
Wolf (*C. lupus*)	UA, US, RAM	12M, 9F, 1U	Adult	29–51 kg	Wild, captive	**22**
Coyote (*C. latrans*)	UA, RAM	4M, 2F	Adult	Unknown	Wild	**6**
Coydog (*C. latrans x familiaris*)	RAM	3M, 1F	Adult	Unknown	Wild	**4**
Total		**47M, 24F, 3U**				**74**

[a] **UA** is the Zooarchaeological reference collection, Department of Anthropology, University of Alberta; **USask** is the Zooarchaeological reference collection, Department of Anthropology, University of Saskatchewan; **CMN** is the Canadian Museum of Nature; **RAM** is the Royal Alberta Museum.
[b] M-male, F-female, U-unknown.

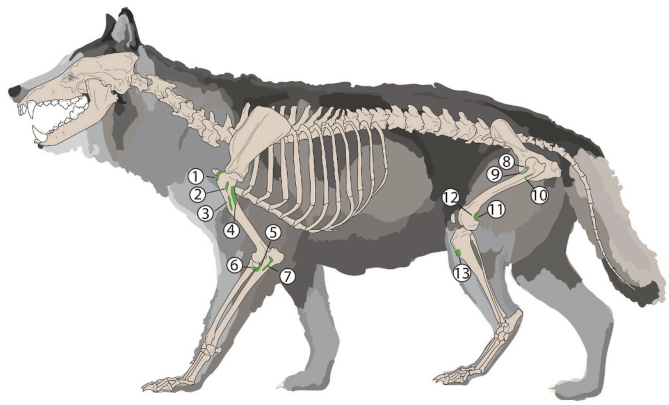

Fig. 1. Entheses examined for this study. 1) *Supraspinatus*; 2) *Teres minor*; 3) *Deltoideus*; 4) *Teres major/Latissimus dorsi*; 5) *Anconeus*; 6) *Biceps brachii*; 7) *Brachialis*; 8) *Iliopsoas*; 9) *Vastus medialis*; 10) *Vastus lateralis*; 11) *Gastrocnemius* medial head; 12) *Gastrocnemius* lateral head; 13) *Sartorius/Gracilis/Semitendinosus.* Figure created by Hailey Kennedy.

morphological variability (Fig. 2). All terminology, definitions, and score descriptions were compiled into a manual that included photographs of examples and anatomical diagrams of muscles associated with each enthesis (Appendix B).

Observer error tests were conducted to assess the agreement between different recording sessions for a single observer (intra-observer error) and among two or more separate observers (inter-observer error). The former involved four experienced observers (the authors) over two sessions spaced by at least three weeks using a sample of sled dogs (n = 15) and pet dogs (n = 15), totalling 390 entheses scored. The latter involved the experienced observers and a group of seven inexperienced student volunteers who, during two-day sessions, each scored 39 entheses on a sample of ten pet dogs. For the student group, the scoring protocol was presented by the first author (JS) and a simplified manual was provided. Levels of agreement were recorded as percentages. Cohen's kappa was used to measure the strength of agreement when comparing up to two observers, and Fleiss's kappa was used to compare the strength of agreement for all participants following Landis and Koch (1977).

Following observer testing, all canid specimens (n = 74) were scored by the first author, totalling 939 attachment sites documented. Only one (left or right) enthesis was scored for each specimen. Entheses with pathological conditions (e.g., osteoarthritis) or attachments obscured by soft tissues were excluded. For each of the 13 entheses considered, scores (1–2 or 1–3) were calculated as frequencies (percentages). For example, 34 of the 74 canid specimens received *supraspinatus* scores of 1 (45.9 %) and 40 received scores of 2 (54.1 %). Kruskal-Wallis *H* tests and pairwise comparisons (Dunn's tests) were used to compare scores within and between activity groups (i.e., sled dogs, pet dogs, and wild canids; Dunn and Jean, 1961; Kruskal and Wallis, 1952). Wilcoxon-signed rank tests were used to compare scores between the forelimb and hindlimb, and between FE and FCE (Wilcoxon, 1945). Because confounding factors are known to influence entheseal morphology for both humans and non-humans (e.g., Bindé et al., 2019; Henderson et al., 2017; Salmi and Niinimäki, 2016; Sick, 2021), the relationships between EC scores and age, sex, and body mass were also evaluated. EC scores for male and female canids were compared using correlational coefficients (r_s) and Mann-Whitney U tests (Mann and Whitney, 1947; Spearman, 1904). Likewise, age was evaluated (for dogs) by both age category (adult, <6 years vs. older adult, 6+ years) and by known age in years, using Mann-Whitney U tests and Spearman's correlation, respectively. Finally, the influence of body mass on entheseal morphology was evaluated by analyzing correlations with estimated weights (kg) calculated using formulae developed for dogs and wolves (Losey et al., 2017). Since formulae were not available for coyotes and coydogs, correlations with femoral head breadths (mm)—the same measurement used to calculate estimated weight—were used as a proxy for body mass to include all wild canids (Appendix C). Correlation strength thresholds of r_s are as follows: 0.10–0.29 = Weak; 0.30–0.49 = Moderate; 0.50–1.0 = Strong (Cohen, 1988). For all statistical tests, significance was set at $\rho < 0.05$. Score frequencies and percentages were calculated using Microsoft Excel version 16.76 (2023), and statistical tests were calculated using IBM SPSS statistics 29.0.1 (2023).

3. Results

3.1. Observer error

Total intra-observer agreement averaged 82 %, with the kappa of Cohen showing 'moderate' to 'substantial' agreement (κ = 0.66 average). Agreement strength varied depending on observer and ranged from poor to perfect for each enthesis (Table 2). Some attachment sites were relatively high in agreement strength for all observers, such as *teres minor* (substantial– perfect), while others had low and high agreement depending on the observer, such as *vastus medialis* (fair to near perfect) Total inter-observer error strength for both observer groups was 'moderate' (κ = 0.42–0.58), but higher, ranging from fair to substantial, among experienced observers (Table 3).

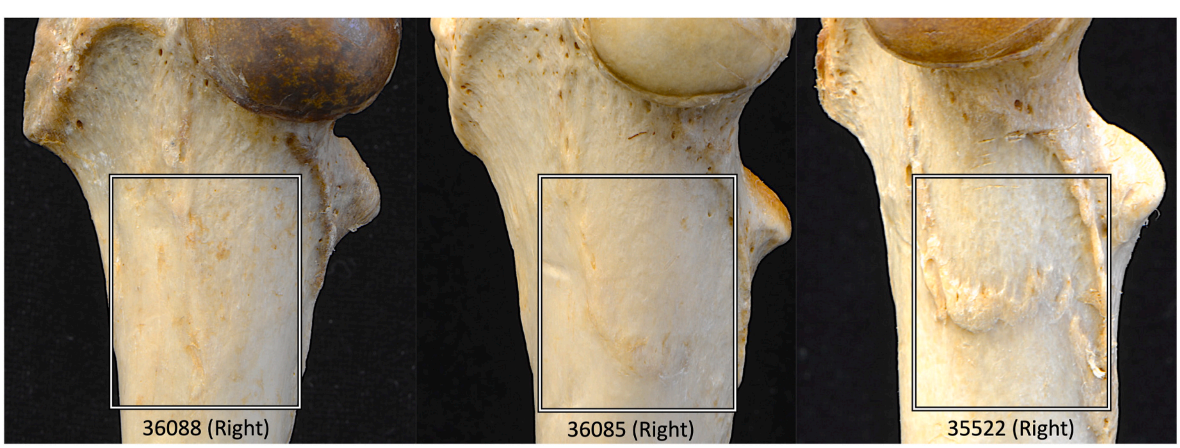

Fig. 2. Example of scores 1 to 3 (left to right) for *vastus medialis* on the proximal femur. Scoring margins are within white boxes. CMN specimen number and element side are indicated.

Table 2
Results of the intra-observer error testing.

Enthesis	N	Agreement, Average	κ (Cohen), Average	Quality of Agreement
Supraspinatus	30	76 %	0.51	Moderate
Deltoideus	30	80 %	0.46	Fair–Substantial
Teres minor	30	93 %	0.82	Substantial–Perfect
Teres major/ Latissimus dorsi	30	78 %	0.53	Moderate–Substantial
Anconeus	27	89 %	0.76	Moderate–Perfect
Brachialis	27	86 %	0.73	Moderate–Near perfect
Biceps brachii	28	87 %	0.72	Moderate–Near perfect
Sartorius/ Gracilis/ Semitendinosus	27	86 %	0.72	Moderate–Perfect
Iliopsoas	28	75 %	0.47	Poor–Substantial
Vastus medialis	28	73 %	0.51	Fair–Near Perfect
Vastus lateralis	28	88 %	0.58	Fair–Substantial
Gastrocnemius, medial head	28	83 %	0.65	Moderate–Substantial
Gastrocnemius, lateral head	28	83 %	0.63	Moderate–Substantial
Total	**369**	**82 %**	**0.66**	**Moderate–Substantial**

3.2. Score analysis

Score frequencies can be found in Table 4. Score distribution varied widely by attachment site and activity group. Scores for all wild canid species are considered together because results between wolves and coyotes/coydogs were not significantly different. Sled dogs showed the highest score frequencies overall and were significantly higher than both pet dogs ($\rho = 0.018$) and wild canids ($\rho < 0.001$), who had lower scores that did not differ significantly from one another ($\rho = 0.455$). Scores for seven entheses were significantly higher among sled dogs (Fig. 1). For four of these entheses—*gastrocnemius* (medial head), *deltoideus, vastus medialis,* and *brachialis*—sled dogs had higher scores than both pet dogs and wild canids. Sled dogs also had higher scores than wild canids for *supraspinatus* and *biceps brachii*, and higher scores than pet dogs for *gastrocnemius* (lateral head). Comparing enthesis type and limb position (Table 5), FCE generally scored higher than FE for all canids except one wolf, and forelimb entheses scored higher than hindlimb ones for all but ten individuals (one sled dog, two pet dogs, five wolves and two coyotes/coydogs).

3.3. Confounding factors

3.3.1. Age

Total score frequencies showed that older adult (6+ years) sled dogs had higher scores than adults (<6 years), while the opposite trend was found for pet dogs (Table 6). Mann-Whitney U tests found no significant differences comparing scores between adult and older adult dogs, but sled dogs had a moderately positive correlation between known age and EC scores overall ($\rho = 0.04$; $r_s = 0.475$) and between known age and *gastrocnemius* (medial head) scores ($\rho = 0.016$; $r_s = 0.52$). Pet dogs also showed a moderately positive correlation with age for the *gastrocnemius* (medial head) scores ($\rho = 0.047$; $r_s = 0.488$).

3.3.2. Sex

Male canids had higher scores than females on average, though score gaps between males and females were largest among sled dogs and wild canids, with male-female score differences of 9 % and 5.7 %, respectively (Appendix D). In contrast, female pet dogs scored 6.3 % higher than males. Only *vastus lateralis* was significantly different between all males and females ($\rho = 0.033$), where female canids had higher score 2 frequencies (41.7 %) than males (17.8 %), especially pronounced among sled dogs (60 % versus 6.3 %). Correlations for *vastus lateralis* found this score disparity to be significant but weak among all females ($\rho = 0.032$, $r_s = 0.259$) but strong among sled dogs ($\rho = 0.006$; $r_s = 0.583$). Sled dogs also had a strong negative correlation for *sartorius/gracilis/semitendinosus* ($\rho = 0.013$; $r_s = -0.531$), where higher scores of 2 and 3 favoured males compared to females. Correlations for *deltoideus* were marginally significant among wild canids ($\rho = 0.055$; $r_s = -0.349$), where males were more likely to score 2 than females.

3.3.3. Body mass

All significant correlations between EC scores and body mass (both estimated weight and femoral head breadth measurements) were positive, indicating that scores increased as body mass increased (Table 7). Note that significance (ρ) and correlation coefficients (r_s) for dogs and wolves were identical for both sets of results because femoral head breadth measurements (mm) were the only variable used to calculate estimated weight (kg). Among all canid groups, coyotes and coydogs had the smallest average body size, followed by pet dogs who were just as small on average but ranged considerably larger, while sled dogs were larger and closer in weight to wolves, who were the largest (Table 8).

Total EC scores were moderately correlated with body mass among all canids ($\rho = 0.003$; $r_s = 0.349$), including *teres minor* ($\rho = 0.011$; $r_s = 0.295$), *brachialis* ($\rho = 0.01$; $r_s = 0.305$), *iliopsoas* ($\rho = 0.05$; $r_s = 0.232$), and *deltoideus* ($\rho = 0.015$; $r_s = 0.283$). Excluding coyotes and coydogs, total scores for dogs and wolves weakly correlated with estimated weight for *deltoideus* ($\rho = 0.03$; $r_s = 0.271$). Within canid groups, individual entheses showed moderate to strong relationships in pet dogs (*brachialis* $\rho = 0.007$; $r_s = 0.61$), sled dogs (*deltoideus* $\rho = 0.035$; $r_s = 0.452$), and wolves (*biceps brachii* $\rho = 0.006$; $r_s = 0.566$), and sled dogs scores were marginally significant in total ($\rho = 0.52$; $r_s = 0.44$). Sample size was likely too small to determine significance among individual entheses for coyotes and coydogs, but total scores were strongly correlated ($\rho = 0.025$; $r_s = 0.698$).

Table 3
Results of the inter-observer error testing.

Enthesis	Experienced Observers (n = 4)			Student Observers (n = 7)		
	N	κ (Fleiss)	Quality of Agreement	N	κ (Fleiss)	Quality of Agreement
Supraspinatus	30	0.42	Moderate	3	0.33	Fair
Deltoideus	30	0.27	Fair	2	−0.04	Poor
Teres minor	30	0.58	Moderate	3	0.51	Moderate
Teres major/Latissimus dorsi	30	0.47	Moderate	3	0.7	Substantial
Anconeus	27	0.64	Substantial	3	0.24	Fair
Brachialis	27	0.64	Substantial	3	0.48	Moderate
Biceps brachii	28	0.68	Substantial	3	0.67	Substantial
Sartorius/Gracilis/Semitendinosus	27	0.47	Moderate	3	0.55	Moderate
Iliopsoas	28	0.33	Fair	3	−0.05	Poor
Vastus medialis	28	0.49	Moderate	3	0.11	Poor
Vastus lateralis	28	0.51	Moderate	3	−0.01	Poor
Gastrocnemius, medial head	28	0.68	Substantial	3	0.59	Moderate
Gastrocnemius, lateral head	27	0.54	Moderate	3	0.38	Fair
Total	**368**	**0.58**	**Moderate**	**38**	**0.42**	**Moderate**

Table 4
EC Score frequencies.

Enthesis	Score	Pet dog n (%)	Sled dog n (%)	Wolf n (%)	Coyote/Coy-dog n (%)	All n (%)
Fibro-Cartilaginous (FCE)						
Teres minor	2	12 (60)	20 (90.9)	6 (27.3)	2 (20)	40 (54.1)
	1	6 (30)	6 (27.3)	1 (4.5)	5 (50)	18 (24.3)
	2	14 (70)	16 (72.7)	21 (95.5)	5 (50)	56 (75.7)
Anconeus	1	4 (22.2)	3 (15)	3 (13.6)	5 (50)	15 (21.4)
	2	14 (77.8)	17 (85)	19 (86.4)	5 (50)	55 (78.6)
Brachialis	1	9 (50)	0 (0)	13 (59.1)	10 (100)	32 (45.7)
	2	9 (50)	20 (100)	9 (40.9)	0 (0)	38 (54.3)
Biceps brachii	1	4 (22.2)	4 (19)	11 (50)	7 (70)	26 (36.6)
	2	14 (77.7)	17 (81)	11 (50)	3 (30)	45 (63.4)
Iliopsoas	1	6 (33.3)	11 (50)	10 (45.5)	10 (100)	37 (51.4)
	2	12 (66.7)	11 (50)	12 (54.5)	0 (0)	35 (48.6)
Gastrocnemius, medial head	1	15 (83.3)	7 (31.8)	17 (77.3)	10 (100)	49 (68.1)
	2	3 (16.7)	15 (68.2)	5 (22.7)	0 (0)	23 (31.9)
Gastrocnemius, lateral head	1	13 (72.2)	7 (31.8)	11 (50)	6 (60)	37 (51.4)
	2	5 (27.8)	15 (68.2)	11 (50)	4 (40)	35 (48.6)
Fibrous (FE)						
Deltoideus	1	17 (85)	11 (50)	17 (77.3)	10 (100)	55 (74.3)
	2	3 (15)	11 (50)	5 (22.7)	0 (0)	19 (25.7)
Teres major/latissimus dorsi	1	5 (25)	2 (9.1)	6 (27.3)	2 (20)	15 (20.3)
	2	15 (75)	20 (90)	16 (72.7)	8 (80)	59 (79.7)
Sartorius/gracilis/semitendinosus	1	2 (11.1)	2 (9.1)	5 (22.7)	3 (30)	12 (17.7)
	2	15 (83.3)	19 (86.4)	16 (72.7)	7 (70)	57 (79.2)
	3	1 (5.6)	1 (4.5)	1 (4.5)	0 (0)	3 (4.2)
Vastus medialis	1	10 (55.6)	2 (9.1)	12 (60)	6 (60)	30 (41.7)
	2	8 (44.4)	18 (81.8)	10 (40)	4 (40)	40 (55.6)
	3	0 (0)	2 (9.1)	0 (0)	0 (0)	2 (2.8)
Vastus lateralis	1	14 (77.8)	18 (81.8)	14 (63.6)	8 (80)	54 (75.0)
	2	4 (22.2)	4 (18.2)	8 (36.4)	2 (20)	18 (25.0)
Total	**1**	**113 (46.7)**	**75 (26.7)**	**136 (47.6)**	**90 (69.2)**	**414 (44.1)**
	2	**128 (52.9)**	**203 (72.2)**	**149 (52.1)**	**40 (30.8)**	**520 (55.4)**
	3	**1 (0.4)**	**3 (1.1)**	**1 (0.3)**	**0 (0)**	**5 (0.5)**

Table 5
Score ranks for enthesis and limb type using Wilcoxon signed ranks tests ($\rho < 0.001$).

Rank category	Sled dog (n)	Pet dog (n)	Wolves (n)	Coyotes/ coydogs (n)	Total (n)
FCE > FE[a]	20	17	21	10	68
FCE < FE	0	0	0	0	0
FCE=FE	0	0	1	0	1
Forelimb > Hindlimb	19	15	17	8	59
Forelimb < Hindlimb	0	0	2	0	2
Forelimb = Hindlimb	1	2	3	2	8

[a] FCE, fibrocartilaginous entheses; FE, fibrous entheses.

4. Discussion

4.1. Observer error

Overall, *biceps brachii* on the radius had the strongest observer agreement, followed by attachments on the ulna (*anconeus, brachialis)*, humerus (*teres minor*), and femur (*gastrocnemius*). The *deltoideus* (humerus) and *iliopsoas* (femur) had the weakest agreement, while other entheses varied between observer groups. Though there were differences in samples, observers, and session intervals, results show that agreement levels for this method were comparable to—and in some cases higher than—those of other methods developed for human and equid EC. For example, total agreement for the first author (JS) was 84 % compared to 79.7 % for a method developed for equid EC (Bindé et al., 2019, 952). Agreement strengths and kappa values for this method were also similar to those of Bindé and colleagues (2019, 953).

4.2. Activity

Sled dogs had the highest EC scores among canid activity groups, while pet dogs and wild canids had similar scores. This suggests that habitual sled-pulling has a visible influence on canid entheseal morphology overall compared to non-working and wild activity that can be detected using the method. Individual entheses distinctly more expressed in sled dogs have various functions during body movement: *supraspinatus* and *deltoideus* on the humerus, *brachialis* on the ulna, and *biceps brachii* on the radius flex, extend, and stabilize the elbow and shoulder joints to advance the forelimb, while *gastrocnemius* and *vastus medialis* on the femur extend the ankle and knee (Evans and Lahunta, 2013; Smith, 1999). These muscles may have been specially targeted to counter resistant forces as the animals moved forward while harnessed and tethered to sleds, exacerbating EC development through repetitive mechanical stress.

Anatomical and tissue type similarities had consistent effects among all canids. Scores in the forelimb were higher compared to the hindlimb in most canids because the center of gravity in quadrupeds concentrates mechanical loading and weight bearing on the forelimbs more than hindlimbs (Pandy et al., 1988). Fibrocartilaginous entheses (FCE) had higher scores than fibrous entheses (FE) for all canids except one wolf, suggesting that FCE are more sensitive to activity differences. In fact, of the seven entheses that scored statistically higher in sled dogs, five were FCE. This is consistent with other studies (e.g., on humans, Villotte et al., 2010) linking activity more with FCE than FE.

4.3. Confounding factors

Confounding biological factors showed intertwined relationships with canid EC, with each enthesis reflecting age, sex, and body mass to varying degrees. Body mass had the largest influence on canid EC compared to age and sex. Sled dogs showed more statistical relationships with confounding factors than did other canid groups, suggesting

Table 6
Score frequencies and results of Mann Whitney U tests (U) for adult (<6 years) and older adult (6+ years) sled dogs and pet dogs, and correlation coefficients (r_s) with known age in years.

Sled dog				Pet dog		Sled dog		Pet dog	
Enthesis	Score	Adult n (%)	Older adult n (%)	Adult n (%)	Older adult n (%)	ρ (U)	ρ (r_s)	ρ (U)	ρ (r_s)
Fibro-Cartilaginous (FCE)									
Supraspinatus	1	2 (15.4)	0 (0)	2 (33.3)	6 (42.9)	0.556 (49.5)	0.29 (0.242)	0.779 (38)	0.72 (−0.088)
	2	11 (84.6)	9 (100)	4 (66.7)	8 (57.1)				
Teres minor	1	3 (23.1)	3 (33.3)	2 (33.3)	4 (28.6)	0.695 (52.5)	0.651 (−0.105)	0.904 (40)	0.501 (−0.165)
	2	10 (76.9)	6 (66.7)	4 (66.7)	10 (71.4)				
Anconeus	1	2 (15.4)	1 (14.3)	2 (33.3)	2 (16.7)	1 (45)	0.354 (0.225)	0.616 (30)	0.268 (0.285)
	2	11 (84.6)	6 (85.7)	4 (66.7)	10 (83.3)				
Brachialis	1	0 (0)	0 (0)	2 (33.3)	7 (58.3)	1 (45.5)	– (–)	0.437 (27)	0.281 (−0.278)
	2	13 (100)	7 (100)	4 (66.7)	5 (41.7)				
Biceps brachii	1	3 (23.1)	1 (12.5)	0 (0)	4 (33.3)	0.697 (46.5)	0.681 (0.098)	0.291 (24)	0.957 (−0.014)
	2	10 (76.9)	7 (87.5)	6 (100)	8 (66.7)				
Iliopsoas	1	6 (46.2)	5 (55.6)	1 (16.7)	5 (41.7)	0.774 (53)	0.493 (0.158)	0.437 (27)	0.303 (−0.266)
	2	7 (53.8)	4 (44.4)	5 (83.3)	7 (58.3)				
Gastrocnemius, medial head	1	6 (46.2)	1 (11.1)	5 (83.3)	10 (83.3)	0.186 (38)	**0.016 (0.52)**[a]	1 (36)	**0.047 (0.488)**[a]
	2	7 (53.8)	8 (88.9)	1 (16.7)	2 (16.7)				
Gastrocnemius, lateral head	1	5 (38.5)	2 (22.2)	4 (66.7)	9 (75)	0.556 (49)	0.071 (0.402)	0.82 (33)	0.685 (−0.106)
	2	8 (61.5)	7 (77.8)	2 (33.3)	3 (25)				
Fibrous (FE)									
Deltoideus	1	7 (53.8)	4 (44.4)	6 (100)	11 (78.6)	0.744 (53)	0.785 (0.063)	0.494 (33)	0.298 (0.252)
	2	6 (46.2)	5 (55.6)	0 (0)	3 (21.4)				
Teres major/latissimus dorsi	1	2 (15.4)	0 (0)	1 (16.7)	4 (28.6)	0.566 (49.5)	0.29 (0.242)	0.718 (37)	0.789 (−0.066)
	2	11 (84.6)	9 (100)	5 (83.3)	10 (71.4)				
Sartorius/gracilis/ semitendinosus	1	2 (15.4)	0 (0)	1 (16.7)	1 (8.3)	0.794 (54)	0.128 (0.343)	0.616 (30.5)	0.921 (0.026)
	2	10 (76.9)	9 (100)	5 (83.3)	10 (83.3)				
	3	1 (7.7)	0 (0)	0 (0)	1 (8.3)				
Vastus medialis	1	1 (7.7)	1 (11.1)	3 (50)	7 (58.3)	0.512 (48.5)	0.304 (0.235)	0.82 (33)	0.815 (−0.061)
	2	12 (92.3)	6 (66.7)	3 (50)	5 (41.7)				
	3	0 (0)	2 (22.2)	0 (0)	0 (0)				
Vastus lateralis	1	10 (76.9)	8 (88.9)	3 (50)	11 (91.7)	0.647 (51.5)	0.406 (−0.191)	0.18 (21)	0.127 (−0.385)
	2	3 (23.1)	1 (11.1)	3 (50)	1 (8.3)				
Total	**1**	**49 (29)**	**26 (23.2)**	**32 (41)**	**81 (49.4)**	0.311 (32.5)	**0.04 (0.475)**[a]	0.591 (27)	0.609 (−0.138)
	2	**119 (70)**	**84 (75)**	**46 (59)**	**82 (50)**				
	3	**1 (0.6)**	**2 (1.8)**	**0 (0)**	**1 (0.6)**				

[a] $\rho < 0.05$.

Table 7
Correlation between EC score and femoral head breadths (Hbr) using Spearman's Rho for all canids.

Enthesis	Pet dog ρ (r_s)	Sled dog ρ (r_s)	Wolf ρ (r_s)	Coyote/Coydog ρ (r_s)	All (Est. weight in kg) ρ (r_s)	All (Hbr in mm) ρ (r_s)
Fibro-Cartilaginous (FCE)						
Supraspinatus	0.824 (0.053)	0.373 (0.2)	0.669 (0.097)	0.631 (0.174)	0.364 (−0.115)	0.889 (−0.017)
Teres minor	0.634 (0.114)	0.776 (−0.064)	0.594 (0.12)	0.924 (0.035)	0.087 (0.216)	**0.011 (0.295)***
Anconeus	0.684 (−0.103)	0.721 (0.085)	0.747 (0.073)	0.497 (0.244)	0.387 (0.114)	**0.057 (0.288)***
Brachialis	**0.007 (0.61)***	– (–)	0.225 (0.27)	– (–)	0.179 (0.176)	**0.01 (305)***
Biceps brachii	0.412 (0.206)	0.185 (0.301)	**0.006 (0.566)***	0.23 (0.418)	0.346 (0.123)	0.134 (0.18)
Iliopsoas	0.317 (0.25)	0.109 (0.351)	1 (0)	– (–)	0.861 (0.023)	**0.05 (0.232)***
Gastrocnemius, medial head	0.955 (0.014)	0.708 (0.085)	0.91 (−0.026)	– (–)	0.449 (0.098)	0.102 (0.194)
Gastrocnemius, lateral head	0.419 (0.203)	0.43 (0.177)	0.924 (−0.021)	0.426 (−0.284)	0.062 (0.239)	0.095 (0.199)
Fibrous (FE)						
Deltoideus	0.722 (−0.085)	**0.035 (0.452)***	0.092 (0.368)	– (–)	**0.03 (0.271)***	**0.015 (0.283)***
Teres major/latissimus dorsi	0.155 (0.33)	0.437 (0.175)	0.474 (−0.161)	0.466 (0.261)	0.902 (0.016)	0.826 (0.026)
Sartorius/gracilis/semitendinosus	0.541 (−0.154)	0.11 (0.351)	0.995 (−0.001)	0.23 (0.418)	0.982 (−0.003)	0.641 (0.056)
Vastus medialis	0.734 (0.086)	0.126 (0.336)	0.656 (0.101)	0.314 (0.355)	0.249 (0.148)	0.21 (0.15)
Vastus lateralis	1 (0)	0.407 (−0.186)	0.228 (0.268)	0.631 (0.174)	0.494 (0.089)	0.255 (0.136)
Total	0.649 (0.119)	**0.052 (0.44)**[a]	0.305 (0.229)	**0.025 (0.698)***	0.141 (0.194)	**0.003 (0.349)***

[a] $\rho < 0.06$ *$\rho < 0.05$.

that working activity significantly interacts with age, sex, and body mass. However, age and body mass also varied between males and females, as did EC scores between activity groups, revealing complex interactions.

Previous studies on humans, reindeer, and equids indicate that older individuals generally show more pronounced EC (Bindé et al., 2019; Niinimäki and Salmi, 2021; Nikita et al., 2019; Nolte and Wilczak, 2013; Salmi et al., 2020). These observations have been attributed to a variety of factors, such as reduction of osteoblastic activity as a by-product of age, the resorption of bone due to muscle underuse, and/or the accumulation of muscle use, mechanical overloading, and acute events of physical trauma through life (Henderson et al., 2017; Michopoulou et al., 2015, 2017; Niinimäki, 2011; Villotte et al., 2010; Villotte and Knüsel, 2014). In our canid sample, EC scores increased with age in sled dogs, but not pet dogs. This highlights the influence of sled-pulling activity and demonstrates the cumulative effect of mechanical stress

Table 8
Averages and ranges of estimated weight and femoral head breadths for all canids.

Species (breed)	Estimated weight (kg)	Femoral head breadths (mm)
Sled dog	39 (avg), 28.4–52.4	24.3 (avg), 21.9–27.2
Pet dog	25.9 (avg), 12.26–41.84	20.5 (avg), 15.7–25
Wolf	42.6 (avg), 29.3–55.4	27.1 (avg), 23.1–30.2
Coyote and Coydog	11.8 (avg), 11.5–12.1[a]	18.1 (avg), 15.9–20.1
Total	**36.2 (avg), 12.3–55.4**	**23.3 (avg), 15.7–30.2**

[a] Combined average body mass between adult male and female coyotes from Jasper National Park, Alberta. Not included in total estimated weights. (Bowen, *Journal of Wildlife Management* 46(1), 201–216, 1982).

throughout life, while suggesting that age-related changes alone have far less influence in comparison. However, the sedentary lifestyles and longevity of pet dogs (average age of 8.5 years) compared to sled dogs in this sample (average age of 4.4 years) make the former group poor representatives for archaeological canids. That said, significant correlations with individual entheses were only noted for the *gastrocnemius* (medial head) in both pet dogs and sled dogs, suggesting that this enthesis may be especially sensitive to age-related changes.

The prominent influence of body mass on EC has been widely observed in studies on humans, reindeer, and equids (Bindé et al., 2019; Foster et al., 2014; Niinimäki and Salmi, 2016; Salmi and Niinimäki, 2016; Salmi et al., 2021; Weiss, 2003, 2004, 2007; Wilczak, 1998; Zumwalt, 2006). This relationship has been partly attributed to the effect of bone functional adaptation, where larger bodies require larger muscles to meet the basic demands of movement and stability against gravitational forces, by extension affecting entheseal morphology (Foster et al., 2014; Ruff et al., 2006; Villotte et al., 2010; Weiss et al., 2012). The effects of body mass are most pronounced on primary weight-bearing limbs (Foster et al., 2014).

Considering canid EC, total scores significantly increased with body mass and generally reflected size differences: coyotes and coydogs had the smallest skeletal measurements and the lowest scores, while sled dogs, pet dogs and wolves had larger measurements and higher scores. Correlations between scores and estimated weight among all dogs and wolves (excluding coyotes and coydogs) are more difficult to observe as their size ranges overlap and interact with variations in scores. Some entheses were more sensitive to body mass than others, and this varied between canid group. For example, while the *deltoideus* was correlated with body mass for all canids, it was especially pronounced for sled dogs. Entheses correlated with body mass were also primarily in the forelimb, which reflects the effect of quadrupedal locomotion concentrating body mass towards the front (Pandy et al., 1988). Overall, total EC scores in sled dogs marginally correlated with body mass, suggesting a compounding effect of body mass and working activity. Since mechanical loading forces are greater on the entheses of larger bodies to counter gravitational forces, then habitual sled pulling exacerbated strain on entheses, affecting EC by extension.

Human EC research has observed that males typically score higher than females, which researchers attribute to a reflection of sexual dimorphism in body mass (Niinimäki, 2011; Weiss, 2003, 2004, 2007, 2015; Weiss et al., 2012). Generally, body mass and sex intertwine due to the influence of physiological differences such as testosterone, which increases muscle mass and body size in males (Foster et al., 2014). However, several human studies found hormonal sex differences to be more impactful on EC morphology, as correlations with body mass disappear when controlling for sex (Weiss, 2004, 2007, 2015; Weiss et al., 2012). Further, EC research in reindeer and equids showed more exaggerated sex differences, where score distributions favoured larger males (Bindé et al., 2019; Niinimäki and Salmi, 2016; Salmi and Niinimäki, 2016; Salmi et al., 2021). The complex interaction of sex and body mass is incompletely understood for non-humans, as species-related differences in anatomy and life history have unknown effects on entheseal morphology (Bindé et al., 2019).

In our canid samples, males generally scored higher than females, especially for sled dogs and wolves, while pet dogs showed the opposite trend. Differences in body mass between males and females were also largest in sled dogs and wolves, and smaller among pet dogs. This suggests the interaction of sex with body mass on entheseal morphology, which is congruent with previous research on reindeer, equids, and humans. The influence of sexual dimorphism in body mass was not visible in pet dogs because they represented males and females of variously-sized breeds, obscuring the influence of sex. The relationship between body mass and sex was especially significant for *deltoideus,* which correlated with body mass and sex, though only in wild canids to a marginal extent. However, not all entheses that correlated with sex—or differed between males and females—also correlated with body mass. Therefore, entheses correlating with sex could reflect the impacts of body size, sex hormones, or both on canid entheseal morphology.

Working activity may further influence the effect of sex hormones on canid EC. For example, *sartorius/gracilis/semitendinosus* was only significantly correlated with sex among sled dogs, so the role of testosterone may have a larger impact as muscles adapt to consistent habitual activity (Foster et al., 2014). However, the influence of sexual dimorphism on entheseal morphology in canids remains unclear from these results. Furthermore, age differences between males and females in the canid sample may influence results: female canids were younger than males and had significantly higher *vastus lateralis* scores, where score disparities and age differences were highest among sled dogs. As *vastus lateralis* did not correlate with body mass, this could suggest an unexpected age-related influence on this enthesis or an unknown interference in the data that caused statistical significance. Either way, the sample size was too limited to draw more definitive conclusions.

4.4. The scoring method: benefits, limitations, and recommendations

In general, the results of this visual scoring method have provided important information regarding the effect of habitual activity and confounding factors on canid EC. Sled pulling had a significant and visible influence on canid EC that was revealed by the scoring method, particularly for muscles used to flex, extend, and stabilize the shoulder, ankle, and knee. Further, working activity visibly impacted the influence of confounding factors on canid EC beyond those of non-working and wild canids. It also revealed the impact of anatomical and tissue type similarities on canid EC across all species and activity histories: FCE appeared more sensitive to morphological changes than FE, and body mass had a large impact on entheseal morphology, which in canids concentrates mechanical loading in the forelimb. Males that were larger than females also typically showed higher scores, implying that sexual dimorphism played a significant role, though the influence of sex hormones apart from body mass remains unclear. All factors likely affected entheseal morphology, but some entheses had better observer repeatability than others. This presents benefits and limitations to using this method as a way to identify sled pulling activity in archaeological contexts.

Entheses that are highly expressed in sled dogs and have high observer agreement are the strongest indicators of working activity. *Brachialis* on the ulna, for example, is an especially useful attachment for study because it has high observer agreement, and all sled dogs present a distinctly raised distal margin, while only half of pet dogs and fewer than half of wild canids shared the same feature. *Gastrocnemius* (medial head) on the femur also had high observer agreement and is significantly more expressed in sled dogs. Other attachments, such as *biceps brachii* and *gastrocnemius* (lateral head), had good observer agreement, but were not significantly different from pet dogs or wild canids, respectively. *Deltoideus* and *vastus medialis* scored high in sled dogs compared to other activity groups but were among the lowest in observer agreement, while *supraspinatus* had low observer error and differentiated sled dogs only from wild canids. Entheses that were sensitive to confounding factors may also obscure relationships between EC and activity. For example, *brachialis, biceps brachii,* and *deltoideus* correlated with body mass among activity groups independently or all together, while *gastrocnemius* (medialis) correlated with age in both pet dogs and sled dogs. Therefore, higher scores in these attachments should be regarded with caution.

Given these overall EC patterns, we recommend considering all 13 entheses whenever possible to identify habitual sled pulling activity. Though the availability or preservation of canid remains found in archaeological contexts will impact the reliability of EC data, this method does not require whole specimens or elements, only an observable enthesis. Additionally, the combination of EC scores with other material remains such as sled parts, harnesses, and tackle, or broader environmental and historical information add further context to reconstruct activity. As such, recording multiple entheses to compare with multiple individuals increases the validity of data to differentiate working from non-working and wild canids. Particular attention should given to the *brachialis* (ulna) and medial head of the *gastrocnemius* (femur), followed by the *deltoideus* (humerus) and *vastus medialis* (femur). The latter two should be interpreted more cautiously. Scores for all other entheses studied here appear to be less reliable individual indicators of sled pulling activity. Table 9 ranks the effectiveness of those entheses that were significantly associated with sled-pulling activity.

There are also inherent problematic aspects pertaining to the use of observational scoring methods for EC, such as their propensity for observer bias and low statistical power due to the small number of score ranks used. However, this method demonstrates observer error rates equivalent to—and sometimes better than—other scoring methods in humans and equids, and the scoring method has successfully differentiated working from non-working and wild canids overall and for several entheses (Bindé et al., 2019; Henderson et al., 2013). Thus, preliminary results from this method meet the current standards set for other observational methods.

Other limitations to this study pertain to the canid sample and data collection methods used. First, despite the wide variety of canids in this study, modern canids cannot fully reflect archaeological canids. The ages at which dogs began participating in sled pulling in the distant past are unknown. If this occurred significantly later in life than among our sled dog reference sample, entheseal changes related to sled pulling likely would be less pronounced. Differences in the intensity and duration of sled pulling over the course of a dog's life, or even shifts in the weights of loads pulled, would have additional confounding effects upon patterning in entheseal changes. Further, age ranges for pet dogs in this sample reach up to 16 years old, which we suspect is considerably higher than most northern dogs in the past. Second, small sample sizes also limited the choice of statistical methods employed and affected interpretations regarding relationships between activity and confounding factors on entheseal morphology. Relationships such as age comparisons between adults and older adults, for example, were included to accommodate age estimations applied to archaeological dogs, but significance was only identified for age in years. Third, separate evaluations of EC scores according to activity, age, sex, and body mass limit the ability to understand the multifactorial nature of canid EC. Different methods of body mass estimation can also affect interpretations. For example, studies using skeletal measurements as proxies for size found that body mass was one of the largest confounding factors influencing EC morphology, while studies using other methods of body mass estimation did not (Niinimäki, 2011; Weiss, 2003, 2015).

5. Conclusion

Overall, this visual method can reliably differentiate sled-pulling dogs from non-working dogs and wild canids. The observed differences in EC between the sled dogs and the wolves are particularly compelling. Gray wolves are highly cursorial species that inhabited many of the same northern regions where dog sledding occurred historically (Boyd et al., 2023; Mech and Boitani, 2007). In other words, the method appears suitable for distinguishing sled pulling from other forms of high mobility, perhaps including that among dogs that did not pull sleds but nonetheless had very active lives as hunting companions or herding partners. Its suitability for identifying other forms of dog transport, such as cart or travois-pulling, is unknown but worthy of further exploration.

Table 9
Effectiveness of entheses in distinguishing sled-pulling activity.

Rank	Enthesis (number[a])	Explanation
1	all (1–13)	Best practice is to score and consider as many entheses as possible
2	*Brachialis* (7)	High observer agreement, significantly associated with sled dogs, all of which had distinctly raised distal margins
2	*Gastrocnemius*, medial head (11)	High observer agreement, significantly associated with sled dogs
3	*Deltoideus* (3)	Lower observer agreement, significantly associated with sled dogs
3	*Vastus medialis* (9)	Lower observer agreement, significantly associated with sled dogs
4	*Supraspinatus* (1)	Lower observer agreement, significantly associated with sled dogs compared to wild canids only

[a] Corresponding number from Fig. 1.

Entheses were scored using their own characteristics. Because they varied in their tissue type and sensitivity to activity and confounding factors, some attachments were better indicators than others. FCE that express clear and consistent changes, like *brachialis* on the ulna or *gastrocnemius* (medial head) on the femur, may be more dependable for identifying sled-pulling. Others may not adequately capture sled-pulling activity from archaeological remains (e.g., *biceps brachii*), or are better supported with additional EC data to differentiate working from non-working and wild activity (e.g., *vastus lateralis*).

To conclude, the developed method is a useful tool to directly examine activity in canid remains and identify sled dogs from archaeological contexts. It is comparatively reliable to other visual scoring protocols for EC. The study of EC in archaeological dog remains provides an important additional line of evidence to trace out the long-term history of dog sledding and likely other forms of dog-aided mobility. Studies will be particularly informative when combined with evidence of transport-related gear, which often lacks features that clearly identify its use with dogs.

CRediT authorship contribution statement

Jessica Sick: Writing – original draft, Methodology, Formal analysis. **Angela R. Lieverse:** Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Tatiana Nomokonova:** Writing – original draft, Supervision, Methodology, Conceptualization. **Robert J. Losey:** Writing – original draft, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

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Appendix A, B, C, and D. Supplementary data

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